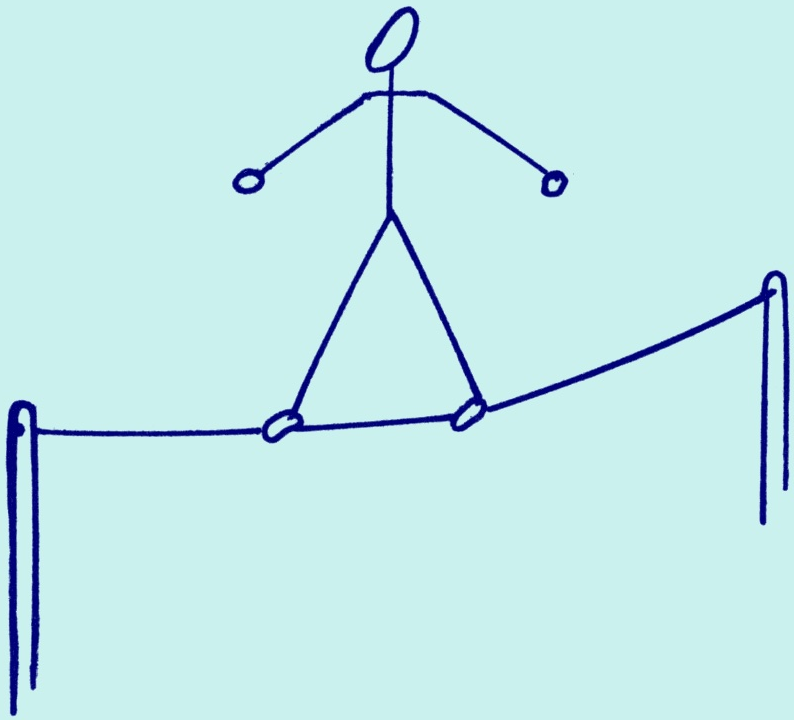
THINGS of science



CENTER OF GRAVITY

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CENTER OF GRAVITY

What is the physical principle that a tightrope walker must apply when he walks with breath-taking daring on a thin wire high above the ground? The same as that applied in the construction of a simple arm balance or a toy doll that always rights itself no matter in which way it is pushed—the appropriate use of the center of gravity.

As we all know, all objects on this earth, both animate and inanimate, or living and nonliving, are acted on by the force of gravity. That is why we manage to remain on the earth's surface even though it is spinning around at high speed and also why we may fall off a ladder if we don't pay attention to it.

Gravity is a part of our lives. All our actions are modified by its force.

In this unit you will do experiments that show you why this is so. You will observe the properties of the center of gravity and their relationship to equilibrium and also how we make use of them.

First check over your specimens.

MODELING CLAY—One piece, wrapped in parchment.

LEAD SINKER—One.

BUCKSHOT—One.

WIRE—One piece 18 inches long.

DRINKING STRAWS—Two.

TOOTHPICKS—Three.

DIAGRAM—One Sheet.

WHAT IS THE CENTER OF GRAVITY?

Newton (1642-1727) long ago formulated the theory of universal gravitation. He stated that every particle in the universe attracts every other particle. Since all objects are made up of tiny particles, all objects also attract each other, and the force of attraction between them, he said, depends upon the number of particles making up the bodies, or their masses, and the distance between them.

Newton expressed this as a law known as the Law of Universal Gravitation which may be stated as follows: Every body in the universe attracts every other body with a force that is directly proportional to the product of their masses and inversely proportional to the square of the distance between them.

In simple terms, it means that the greater the masses of objects, the greater the force of attraction between them and that the closer they are to each other, the stronger this attraction.

The attraction between such objects as a table and chair is very small and under ordinary circumstances is not observed. But the earth because of its great size and mass shows an extremely strong attraction for any object on its surface or near its surface.

Newton also proved that in a sphere of uniform density, the gravitational force exerted is the same as if the mass of the

sphere were concentrated at its center. This is why the gravitational force of the earth tries to pull all objects on its surface toward its center.

This gravitational attraction of the earth gives objects weight. The weight of any body, therefore, is a force and is measured in units of force, such as grams force and pounds force.

The mass of a body on the other hand depends upon the number of particles composing it, or the quantity of material it contains, and is measured in grams or pounds.

The mass of an object always remains the same wherever it is, while its weight may vary depending upon its location. For example, an object will weigh much less on the moon than on the earth although its mass remains unchanged. Why?

Experiment 1. To prove to yourself that weight is a force, hold a heavy book at arm's length in the open palm of your hand. Note the downward force exerted by the book and the great amount of upward force required to hold the book in position. The upward force you exert must equal the downward pull of gravity, or the weight of the book.

The total weight of the book, or of any object, is the sum of the attractive forces acting on each one of its particles (Fig. 1) and can be expressed as a single force W equal to the total of all these forces.

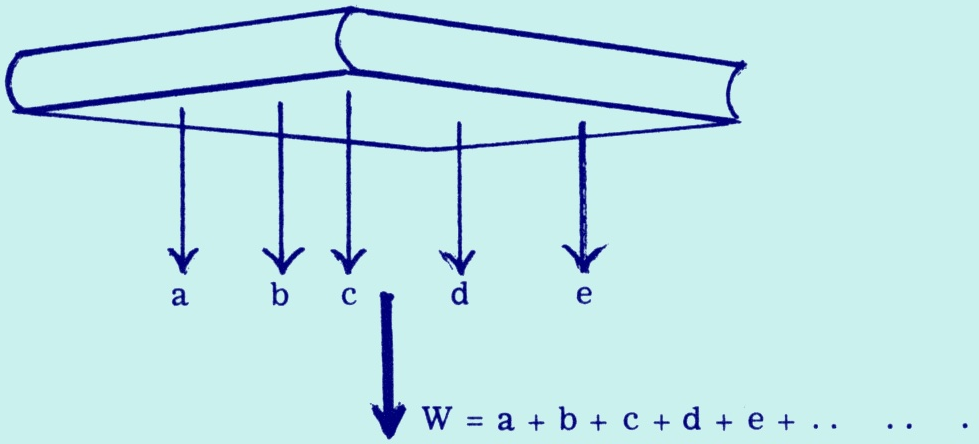

Fig. 1

There is a certain point in any object through which all the forces resulting from the weight of all the particles of the object act. This hypothetical point where the total weight of an object may be assumed to be concentrated is known as the center of gravity. Where is the center of gravity located?

Experiment 2. Cut out the Diagram A from the sheet of diagrams in your unit and paste it on a thin piece of cardboard or other heavy paper so that it is perfectly flat.

Insert a straight pin near one edge of this irregular figure and mark the point A. Twist the pin within the hole slightly to allow the figure to move freely around it. Suspend the figure vertically and note the position at which it comes to rest. When the figure comes to rest, its weight is equally distributed on each side of the

vertical line from the point of suspension and it is in equilibrium.

Make a plumb line using thread and a small weight such as a paper clip or the lead sinker in your unit. Suspend the plumb line from the pin. Mark the point at which the plumb line intersects the bottom edge of the figure point B (Fig. 2a). Draw a straight line from A to B.

Now insert the pin at C. Allow the figure again to find its equilibrium posi-

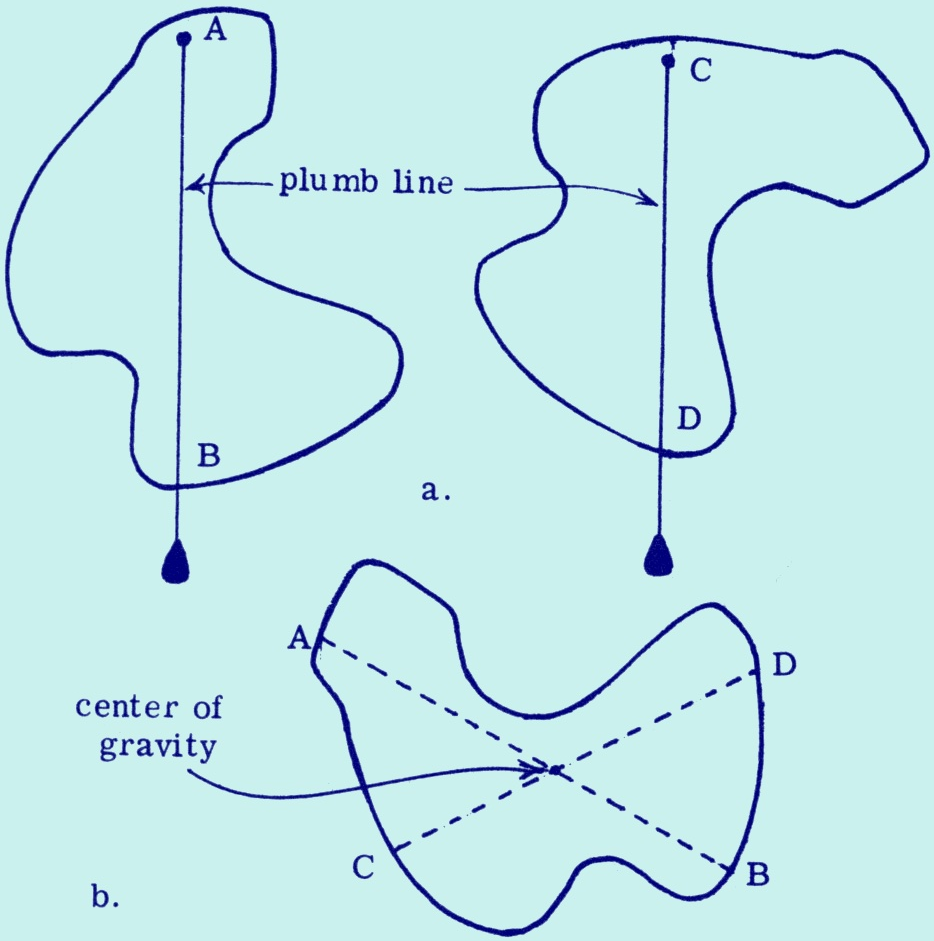

Fig. 2

tion. Locate the vertical line from the pin to the opposite side using the plumb line as before (Fig. 2a). Draw in line CD.

The point at which the two lines intersect (Fig. 2b) is the center of gravity.

Experiment 3. Now hold the figure on a horizontal plane and place the center of gravity on the point of the pin. Does it remain balanced horizontally?

When we consider the weight of a body, we may ignore the fact that the weight is distributed throughout the object and regard the weight as a single force concentrated at the center of gravity (Fig. 2). Thus, a single upward force at that point equal to the downward force, or the weight of the body, will support it.

Experiment 4. Insert your pin in the figure at a third point E and allow it to find its equilibrium position as before (Experiment 2). Does the vertical line pass through the center of gravity? Try suspending the figure from several other locations along the edge. You will find that no matter how many vertical positions you find, all of them will pass through the center of gravity. The center of gravity always lies in the vertical line from the point of suspension of an object.

Since the weight of the figure is equally distributed on each side of all the vertical lines passing through the center of gravity, the figure when balanced on a

pin point at the center of gravity remains horizontal and is in equilibrium.

Move the pin about one-fourth inch from the center of gravity and try to balance the figure horizontally. Is it possible? Why not?

The center of gravity is an important factor in our lives. It must be considered in all construction, large or small, and in most all other areas of our activities. We have had to adjust to it physically. Through trial and error as toddlers we learned to direct our motions in relation to its position in our bodies so that we can maintain our balance whether we stand, walk or stoop. When we neglect it, we have accidents and broken bones. You will understand why this is so as you do the various experiments in this unit.

Experiment 5. It is possible to find the center of gravity of any flat object by suspending it from two different points and finding the point of intersection of its two vertical lines.

Cut out a flat doughnut shape and find its center of gravity. Where is it? Is it in the hole?

The center of gravity may lie within an object or outside it.

Experiment 6. Cut out the chair shape (Diagram B on your sheet of diagrams). Find its center of gravity. Is it outside or inside the object?

The center of gravity always remains

the same for a particular object no matter which way you may turn it, but as you can see, it does not necessarily lie within it.

Experiment 7. Cut out the geometric figures (Diagram C in the sheet of diagrams). Find the center of gravity of each.

Now find the geometric center of each of these figures by drawing diagonals in the parallelogram, rectangle and square, perpendiculars in the triangle and diameters in the circle (Fig. 3).

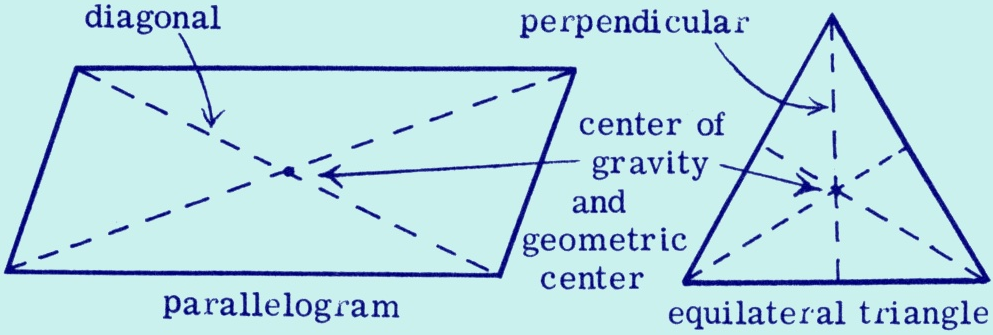

Fig. 3

Do the geometric centers and centers of gravity coincide in all of these cases?

The center of gravity of uniform objects, such as a square, equilateral triangle and circle is always in the geometric center.

Balance these figures on the point of a pin. Can you?

Experiment 8. The center of gravity of any long object may be found by suspending it from a cord. Find the center of

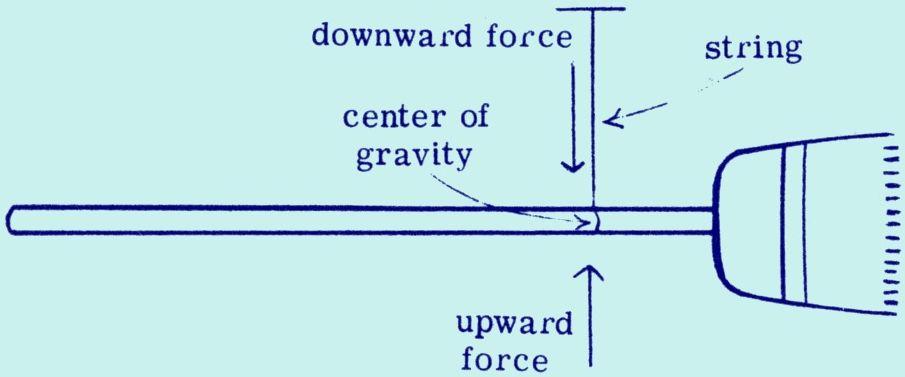

Fig. 4

gravity of a broomstick, hammer or closed umbrella using a strong string or cord. Move the string along the object until it is balanced horizontally (Fig. 4).

When this position is reached, place your finger under the string and lift the broom. Does it remain in equilibrium?

The center of gravity is located at that

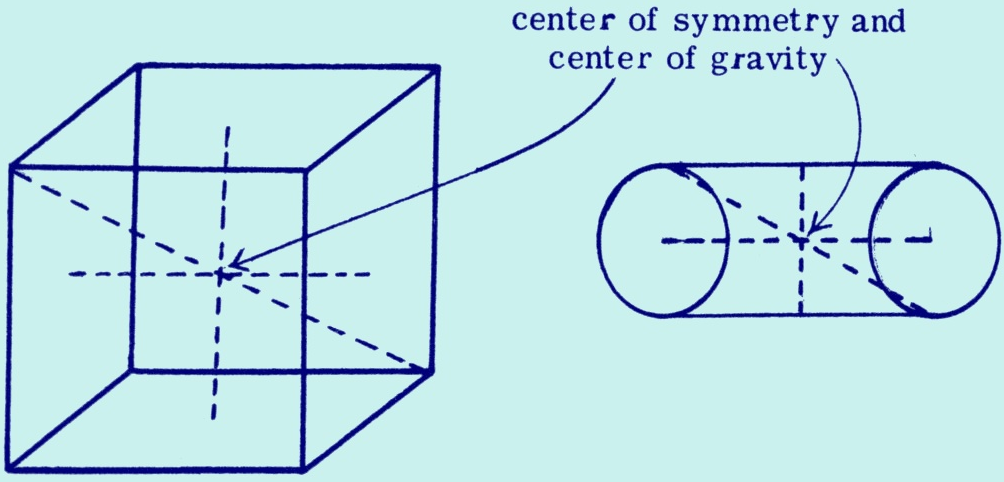

Fig. 5

position. Note that it lies in a vertical line from the point of suspension.

Toward which end of the object is the center of gravity? Why?

Experiment 9. How would you find the center of gravity of an irregular object like a chair?

Experiment 10. In a symmetrical three-dimensional body of uniform weight such as a rod, ball or cube, the center of gravity lies at the center of symmetry. Why? See Figure 5.

THE BALANCE

The function of the familiar beam balance depends upon the proper use of the center of gravity.

When a body is at rest, there is an upward force as well as a downward force acting upon it (Fig. 6a).

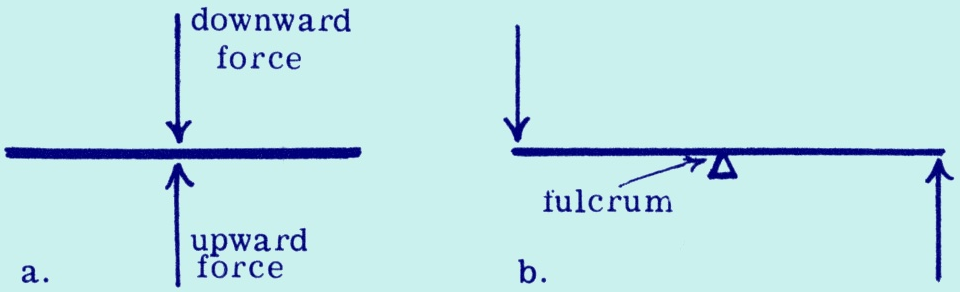

Fig. 6

The two opposing forces may cause two types of movement or displacement, translation and rotation.

If either the upward or downward force of two opposing forces is greater than

the other, an upward or downward movement results. This movement is known as translation.

If a pivoted object, such as the beam of a balance is acted upon by two parallel but oppositely directed (clockwise and counterclockwise) forces, then movement known as rotation occurs (Fig. 6b).

The turning or twisting effect (rotation) caused by a force is known as the moment of force. It is expressed as the product of the force and the length of the lever arm (Fig. 7). Moment of force is also known as the torque.

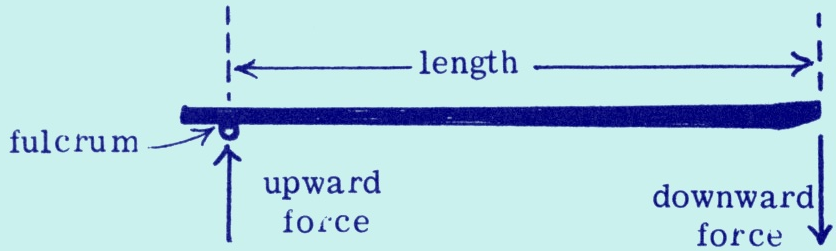

Fig. 7

Experiment 11. If you hold an irregularly shaped pole at any one point between your fingers and do not know the location of the center of gravity, the upward force of the fulcrum (your fingers) and the downward force (the weight of the pole) causes the rod to rotate, and one end will be lower than the other.

However, as you move your fingers along the pole, you will eventually reach a point where the pole will balance on one finger. Your finger then must be directly under the center of gravity and the upward force of your finger is equal to the downward force of the weight of the pole. The two equal forces are in a direct line opposing each other so no rotation occurs. Also, since the pole is in equilibrium the clockwise moment is equal to the counter-clockwise moment and the moment of force equals zero.

Experiment 12. Take a uniform ruler 12 inches long and find its center of gravity. Is it at 6 inches?

In a uniform stick or pole, the center of gravity is at the center, equidistant from both ends.

Experiment 13. Support a ruler or yardstick on an extended finger of each hand at any distance from the center, points A and B (Fig. 8). Now move your fingers toward each other gradually. Where do they meet?

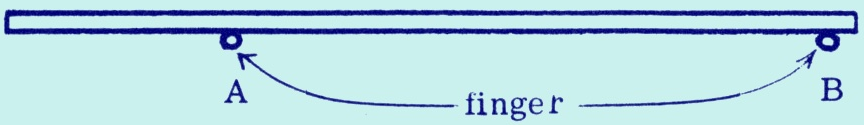

Fig. 8

Now place your fingers at two other points on each side of the center and repeat the experiment. Your fingers will again meet at the center. No matter at what points you start, the two fingers will always meet at the center.

Notice that only one finger at a time moves toward the center (when slowly approached) until the center of gravity is just about reached. Can you explain this?

Place one finger directly under the center of gravity of the ruler and the other next to it. Keeping the ruler exactly in equilibrium and perfectly horizontal, try to move both fingers outward at the same time along the ruler. Can you?

You will find that it is impossible to move the finger directly under the center of gravity, without tilting the ruler, while the other finger can be moved freely back and forth.

Experiment 14. Find the center of

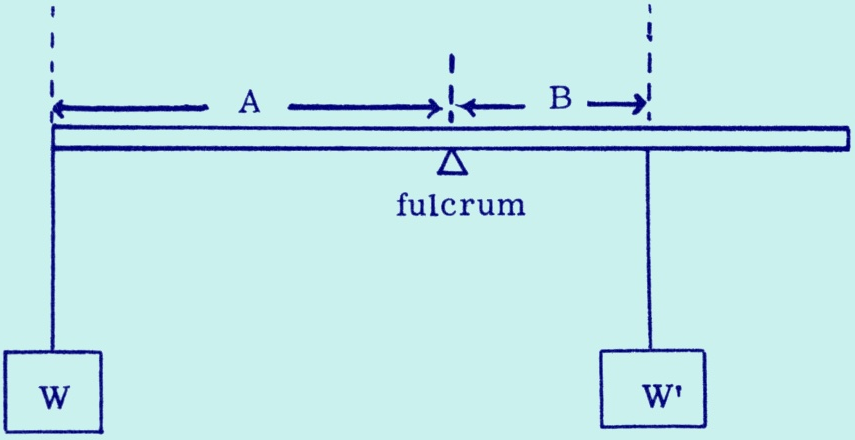

Fig. 9

gravity of various irregular long objects using two fingers as in Experiment 13. Check the center of gravity of each by suspending it from a cord attached to the point at which your fingers met.

The beam balance makes use of the fact that in a rod of uniform dimensions and density, the center of gravity lies at the center. The fulcrum of a balance is always at the center of gravity.

Experiment 15. Suspend one of your drinking straws from a thread attached at its center of gravity to simulate a balance.

In a loaded balance in equilibrium, the load times the length of one arm of the beam is equal to the load on the other arm times the length of that arm (Fig. 9).

In Fig. 9 the balance is in equilibrium because A x W is equal to B x W′. In such balances the weight of the beam is disregarded.

But the beam of a balance does have weight, and knowing the weight of the beam can be very useful.

Experiment 16. Take a small piece of your clay and roll it into a ball. Attach it to one end of the drinking straw. Make another ball of clay about twice the size and attach it to the other end.

Find the center of gravity of this combination by suspending the straw from a thread (Fig. 10).

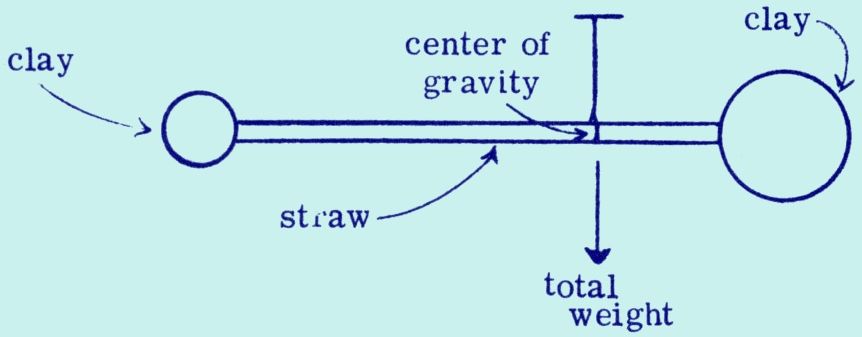

Fig. 10

Since all the weight of an object is concentrated at the center of gravity, we can assume that the total weight of the two pieces of clay act at the center of gravity.

By applying this knowledge, you can find the weight of any object if you know the weight of the balancing stick.

Experiment 17. Weigh a hammer and then find its center of gravity by suspending it from a string. Mark the point A. The total weight of this hammer, say 6 pounds, is concentrated at this point.

Now take any object you wish to weigh and hang it from the end of the handle at C (Fig. 11).

Push the cord along toward the weight until you find a new center of gravity. Mark this point on the hammer B.

Measure the distance between A and B, the two centers of gravity. The length represents the arm for the weight acting at the center of gravity B.

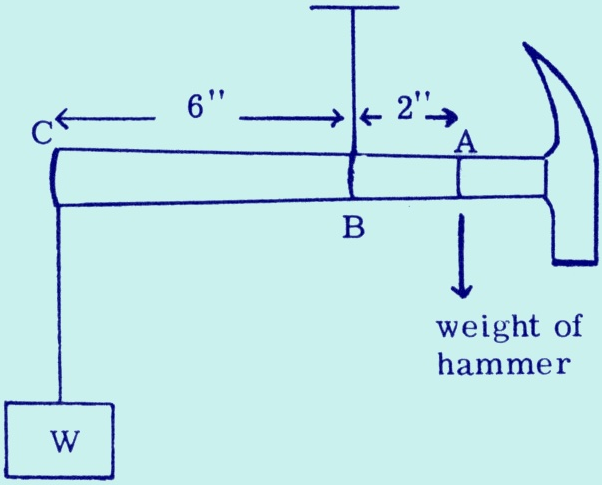

Fig. 11

Measure the distance from B to C. This represents the arm for the weight at C.

To compute the weight W of the object, follow the procedure below.

If BA = 2 inches, BC = 6 inches and the weight of the hammer = 6 pounds, then,

W (weight of the object) x 6 (length of the arm BC) = 6 (weight of the hammer) x 2 (length of the arm BA),

or $6W = 2 \times 6$

and $W = 2$ pounds.

Experiment 18. Now find the weight of a beam of a balance by using the center of gravity.

First find the center of gravity of a stick or ruler. If the ruler is 12 inches long, the center of gravity would be at 6

inches. We can assume that the weight of the ruler is concentrated at this point C (Fig. 12).

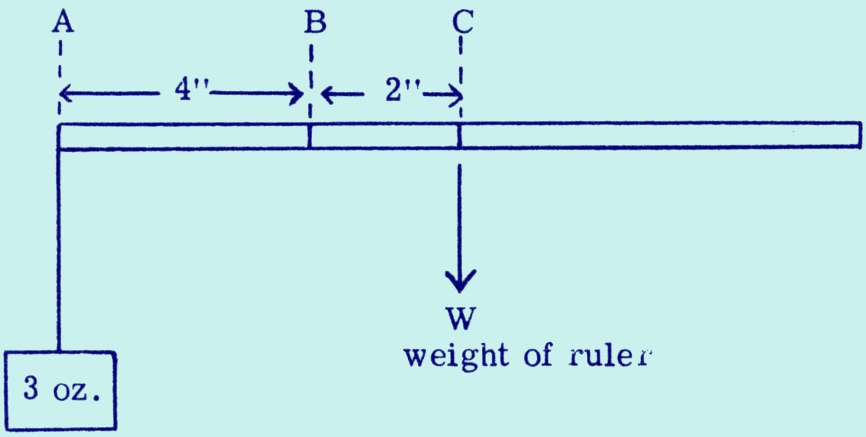

Fig. 12

Hang a known weight (say 3 ounces) from the end A of the ruler.

Now find the new center of gravity with the weight suspended from point A. Mark this B. Measure the distance BC.

The clockwise moment of force is the product of the weight of the ruler W and and the length of the arm BC. If BC is two inches, then you would have 2W.

The opposing moment of force (counterclockwise) consists of a negative amount, the known weight 3 ounces times AB or 4 inches. Since the ruler is in equilibrium the net result of the opposing forces is zero. Therefore,

$$2W - (3 \times 4) = 0$$

or $2W = 12$

$W = 6$ ounces, the weight of the ruler.

Find the weight of a broomstick or any other long object by this method using a known weight such as a pound of sugar.

EQUILIBRIUM

For an object to be in equilibrium, no movement or displacement may take place. To establish this equilibrium, two conditions must be satisfied.

First, the sum of the forces pulling an object up must equal the sum of the forces pulling it down. Then there is no translation.

Second, the sum of the clockwise moments about any point must equal the sum of the counterclockwise moments about the same point. Since the moments then neutralize each other, no rotation is produced.

The center of gravity is an important factor in equilibrium.

If an object is suspended from a cord, its center of gravity must be in the vertical line passing through the point of suspension in order for it to be in equilibrium. If the object in equilibrium is supported from beneath, the center of gravity must lie in the vertical line that passes through the point of support.

Experiment 19. Insert a pin through point A in the irregular figure of Diagram A. Note that it rotates clockwise until it comes to rest. At rest it is in equilibrium

but only in this position, when suspended from A. If suspended from point B, its position at rest would be in equilibrium only in reference to point B.

Now insert a straight pin through the center of gravity. Be sure the figure is perfectly vertical and can move freely around the pin. Note the points A, B, C and D.

Turn the figure so that point A is at the top. Does it remain stationary in this position? Place points B, C and D successively at the top. Does the figure rotate from any of these positions?

You will find that when the point of suspension is the center of gravity, the figure is in equilibrium in all positions. Why?

Now balance the figure on a pin point at the center of gravity. Gently spin it. Note that it remains balanced.

There are three types of equilibrium—stable, unstable and neutral (Fig. 13a).

Experiment 20. Construct two cones from stiff paper and determine the center of gravity of each. You will find that the center of gravity of a cone is a point at ⅓ the distance from its base. Mark the point on the outside of each of the cones.

Place one cone on its base. Now gently push it. Note that it tilts but falls back into its original position.

The cone is in stable equilibrium.

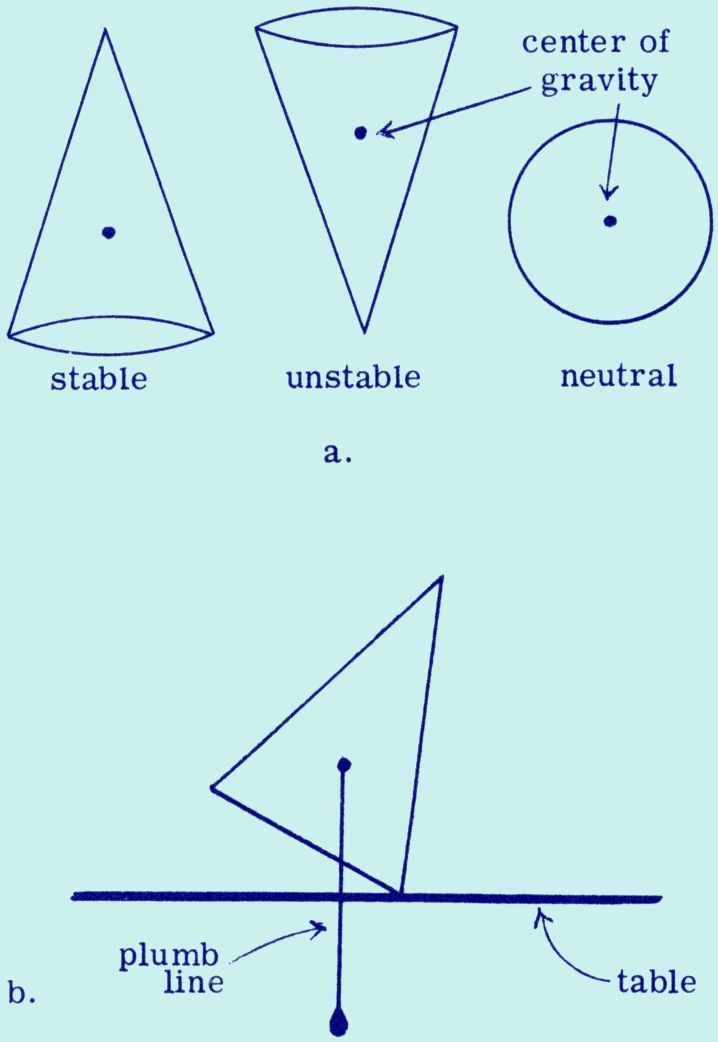

Fig. 13

In stable equilibrium an object if tipped slightly will fall back into its original position.

Experiment 21. Stand the second cone on its tip. You may make it stand, but the slightest touch will cause it to fall.

When an object falls away from its original position when jarred and does

not return to it, it is said to be in unstable equilibrium.

Experiment 22. Push your lead shot gently. Note that it rolls due to the impact, but does not return to its former position nor continue to travel away from its original position. It remains wherever it has been pushed. Such an object is said to be in neutral equilibrium.

A cone lying on its side is also in neutral equilibrium so far as rolling is concerned. Demonstrate this.

Experiment 23. Now tilt the cone standing on its base slightly again. While doing this, observe the mark you made showing the center of gravity. Does the center of gravity travel upward or downward as you tilt the cone?

If the center of gravity of an object is raised when it is tilted, it is in stable equilibrium.

Repeat the experiment with the cone standing on its tip. Does the center of gravity move downward? If the center of gravity is lowered when moved, the object is in unstable equilibrium.

You know that the center of gravity of a sphere is at its center of symmetry.

Roll the lead shot again. Note that its center of gravity is neither lowered nor raised by the movement. An object whose center of gravity remains in the same

position when moved is in neutral equilibrium.

Experiment 24. In order for a body to remain in equilibrium, the center of gravity must always be within its area of support or within its base.

Pass a pin through the center of gravity of one of your cones and hang a light-weight plumb line (thread and paper clip) from it on the outside of the cone. Stand the cone near the edge of a table so that the plumb line can hang freely.

Gradually tilt the cone. Note the exact position of the plumb line when the cone tips over. At what point with reference to the center of gravity does the cone lose its stability? (Fig. 13b).

Experiment 25. Mold your modeling clay into a rectangular shape about ¾ x ½ x 1½ inches. Locate the center of gravity by diagonals. Insert a pin through this point and hang a plumb line from the pin.

Place the clay on its ¾-inch side on the top of your THINGS box with the 1½-inch side flush against the edge so that the plumb line can hang freely (Fig. 14). Now slowly incline the box. Can you predict when the clay will tip over?

Repeat the experiment, but this time stand the clay on the ½ x ¾-inch end.

In which case did the clay tip over sooner? Why?

The broader the area of support and

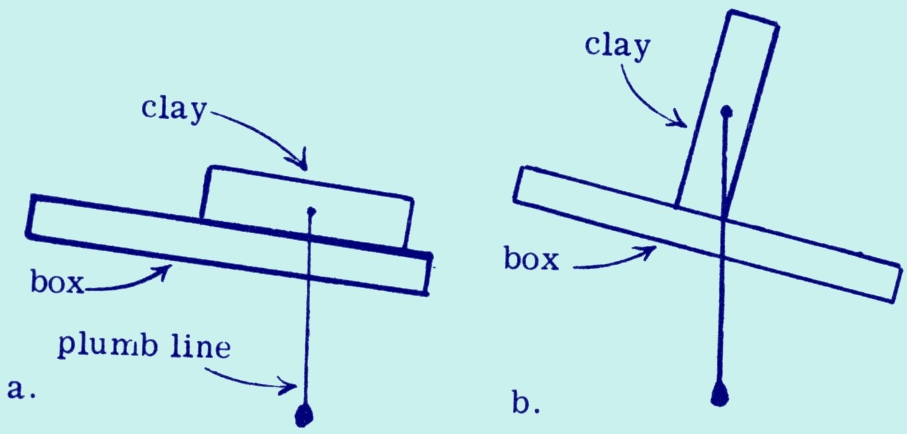

Fig. 14

the lower the center of gravity, the more stable the object.

From this experiment can you surmise the importance of the location of the center of gravity in the construction of automobiles?

Experiment 26. From your observations, can you guess why the leaning Tower of Pisa does not fall?

Experiment 27. In balancing acts, the performer by his movements is always trying to maintain a vertical line from the point of support up through the center of gravity of the objects he is balancing. With this in mind, can you balance a cone or ruler on your finger tip?

Experiment 28. Take your three toothpicks and a small lump of your clay. Insert the toothpicks in the clay to form a tripod.

First have the legs of the tripod as close together as possible and still able to stand upright. How easily does it fall when disturbed?

Gradually widen the base by spreading the toothpicks further apart.

Can you show by diagrams why a broader base makes a tripod more stable?

Experiment 29. A body is in stable equilibrium if a slight disturbance tends to raise its center of gravity.

Make a toy to demonstrate this.

Obtain a cardboard cylinder of about 1½ inches in diameter from the center of a roll of wax paper or other tissue.

Cut a half cylinder section about 1½ inches wide from this. Secure your lead shot to its exact center (Fig. 15a).

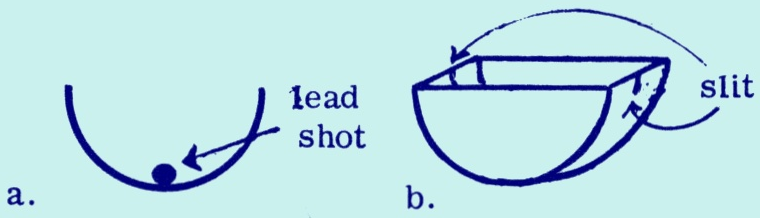

Fig. 15

Next trace and cut out two half circles from cardboard to fit each side of the half cylinder and glue them on (Fig. 15b).

Cut out Diagram D and back it with lightweight cardboard. Color the clown if you wish.

Make a ⅛-inch deep slit at the center

of each end of the cylinder and insert the feet of the figure in them.

Now give the clown a sideways push. It will bounce right back to its upright position. Can you explain why it does so? Is the center of gravity raised or lowered when the toy is tilted?

Experiment 30. A body is in stable equilibrium if the center of gravity is lower than the point of support.

Obtain a piece of stiff cardboard 4 x 1½ inches in size. From your length of wire cut off a piece about six inches long. Insert about one inch of the wire into the cardboard about one-half inch from one edge and equidistant from the two sides. Bend the wire so that the one-inch section lies flat on the surface of the cardboard and then secure it with tape (Fig. 16).

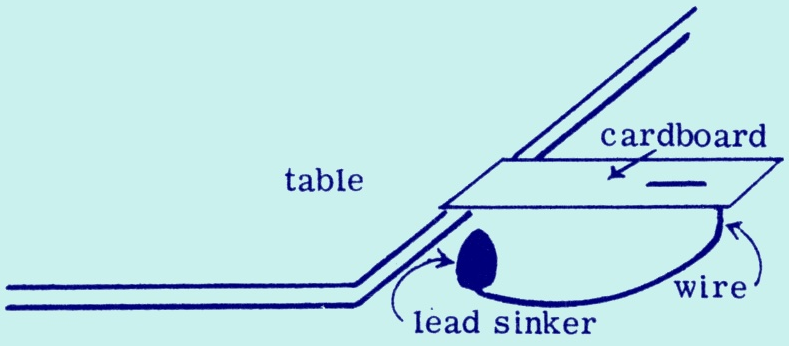

Fig. 16

Bend the other end of the wire up about ¾ inch and insert the lead sinker into it. Push the tip of the wire through

the sinker. Place a small blob of clay over the tip to secure the sinker, or use tape.

Now curve the wire so that the sinker is just below the free edge of the cardboard. Place about one-fourth inch of the cardboard on the edge of a table. Does it remain balanced on the edge of the table? You may have to adjust the position of the weight (the center of gravity) and curve of the wire to obtain equilibrium.

Push down on the cardboard gently. Why doesn't it fall off the table? What does this disturbance do to the center of gravity? Does it raise it or lower it? Where is the center of gravity located in relation to the point of suspension?

Balance the cardboard on the side of a finger. Can you?

Now cut the cardboard an equal width along each side. Does making the strip narrower have any effect on the equilibrium? Why not?

Cut the cardboard about an inch shorter and place it on the edge of the table as before. Why is the cardboard no longer horizontally balanced? Can you adjust the center of gravity so that the cardboard will be horizontal again?

Experiment 31. Using Diagram E, cut two birds out of cardboard, one for each side of the bird. Cut along the dotted line to give more width to the bird's legs for support. Paste the picture of the bird on one of the cardboard figures.

Take the remaining length of wire and secure at least two inches of one end of the wire with tape inside the beak of one side of the bird so that it appears to protrude from the tip of the beak. Then paste the two sides of the bird together except for its feet.

Next obtain a piece of cardboard at least 8 inches or more square. At a midpoint about two inches from one edge of this cardboard cut a hole about ⅛-inch in diameter. Stand the bird on the cardboard by spreading its feet slightly apart and pass the wire from the beak through the hole. Curve the wire toward the back of the bird. Bend up the free end of the wire about ¾ inch from the end and insert your sinker into the wire as in Experiment 30, securing it with clay or tape.

Adjust the weight so that the bird is balanced when its beak is about ¼ inch above the hole. Shape the curve of the wire so that it passes smoothly through the hole when the bird's beak is raised. Note the position of the weight (Fig. 17).

Place the cardboard base with the bird on a table with the hole just outside the edge and the weight unobstructed.

Now push the tail down and the bird will bob up and down as if it were pulling on a worm. What conditions of equilibrium does the toy satisfy?

Experiment 32. The beam of a simple

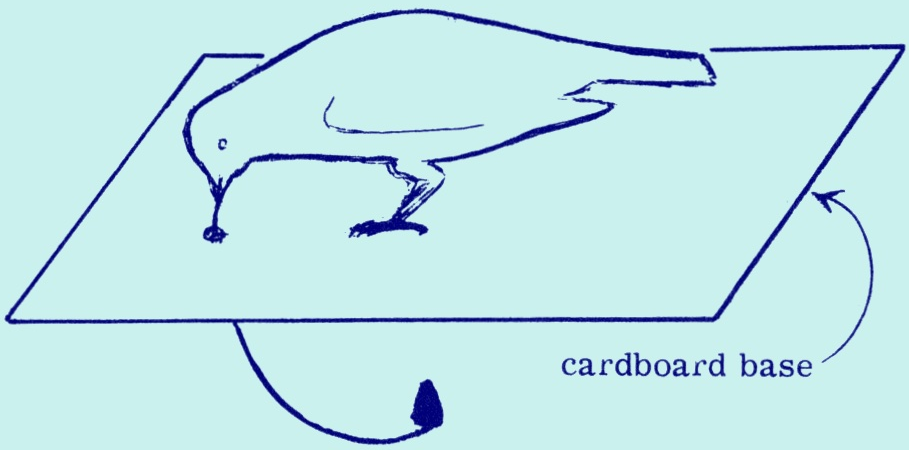

Fig. 17

balance usually rests on a sharp edge with equal arms on each side. However, if a heavy weight is placed on the left arm, the right arm will rise up and the whole unit may tip over.

Suspend one of the plastic straws from the center of gravity to simulate a balance. From one side hang a small weight such as a paper clip. Note how completely unbalanced the beam becomes.

Now take two of your toothpicks and insert them on each side of the point of suspension equidistant from the center of gravity. Make a V-shape and place a small ball of clay at the bottom of the V. Position the clay exactly beneath the center of gravity (Fig. 18).

Place the weight again on the right arm. Does lowering the center of gravity give more stability to the balance?

Most balances are made so that the

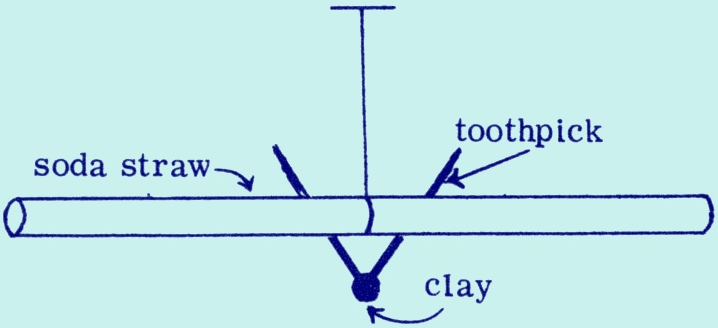

Fig. 18

center of gravity does not lie exactly on the point of support, but just below it.

Experiment 33. Using the knowledge you have acquired about the center of gravity, can you design a humpty dumpty that will never fall off the wall?

How would you balance an orange on the edge of a ruler?

Experiment 34. A cylinder ordinarily rolls down an inclined plane. How would you use center of gravity to prevent it from doing so?

Experiment 35. Here is an experiment that will be fun to try on your friends. Ask one of them to stand with his right side flush against a wall from shoulder to foot. Tell him to keep his feet together. Now ask him to lift his right foot as high as possible. He does this with ease. Next tell him to lift his left foot as high. Can he? Can you explain why he cannot?

As you have observed, any object will

remain in equilibrium as long as its center of gravity is in the right position with respect to the object.

Using your ingenuity and creativity you can devise many other experiments to demonstrate the properties of the center of gravity, and also design various toys applying its principles.

If you wish to delve further into the subject, various physics textbooks will be helpful.

Appreciation is expressed to the Diamond International Corporation, Diamond Match Division, New York, for contributing the toothpicks for this unit.

* * *

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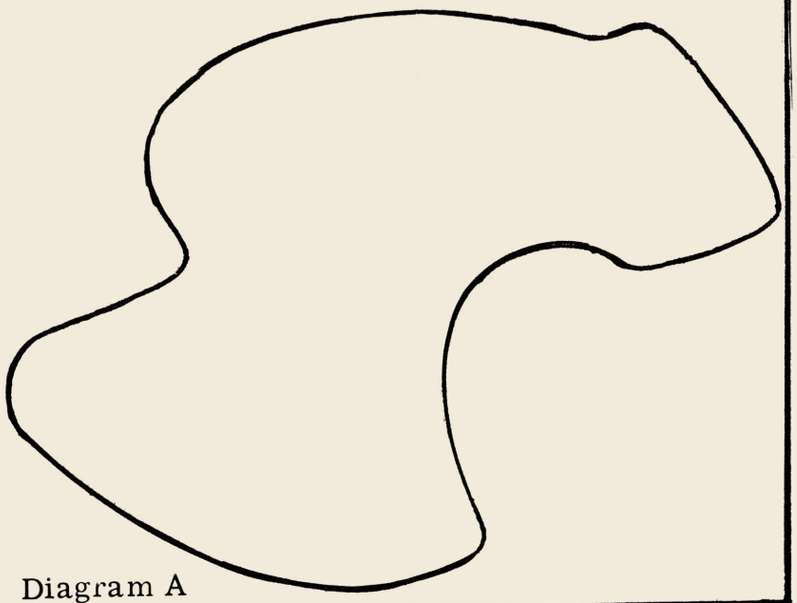

Diagram A

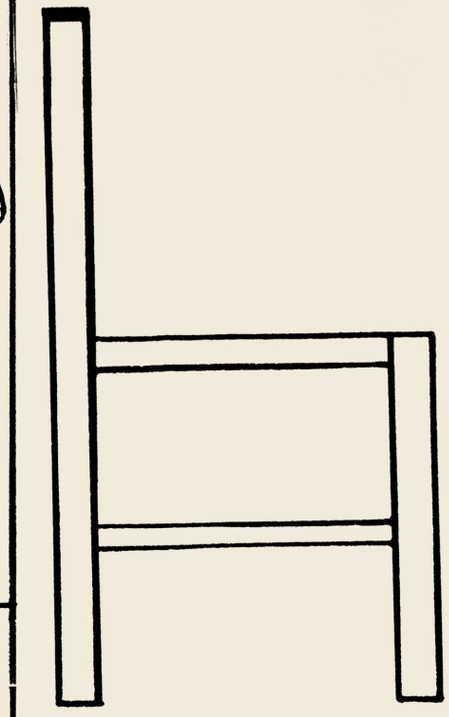

Diagram B

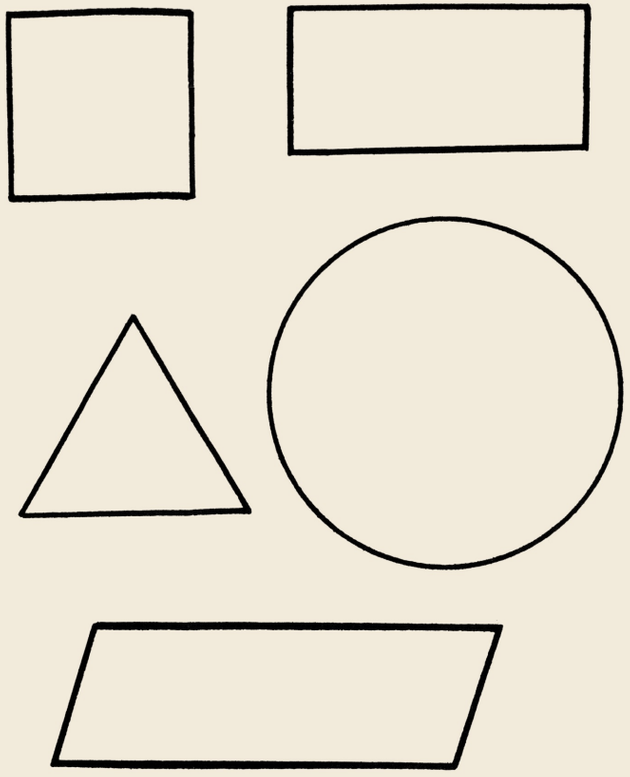

Diagram C

Diagram D

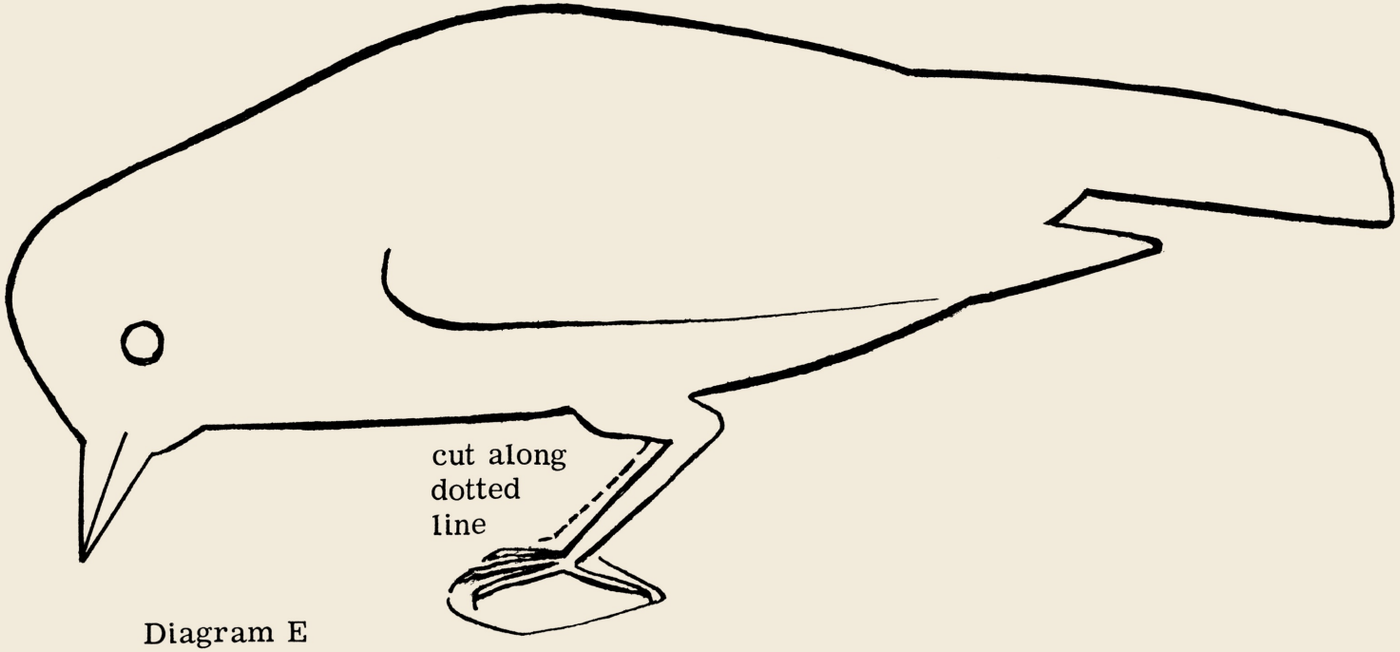

Diagram E

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